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LIFE CYCLE IMPACT ASSESSMENT

Development of impact factors on damage to health by infectious diseases caused by domestic water scarcity

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Abstract

Background, aim, and scope Water scarcity is a critical environmental issue. In particular, domestic water is a necessary resource for our fundamental activities, and poor water quality may lead to damage to health caused by infectious diseases. However, there is no methodology to assess the damage of domestic water scarcity (low accessibility to safe water) caused by water consumption. The main objectives of this study are to model the health damage assessment of infectious diseases (ascariasis, trichuriasis, hookworm disease, and diarrhea) caused by domestic water scarcity and calculate damage factors on a country scale.

Materials and methods The damage to health caused by infectious diseases was assumed to have resulted from domestic water scarcity due to loss of accessibility to safe water. Damage function of domestic water scarcity was composed of two steps, including assessments of water accessibility and health damage. This was modeled by applying regression analyses based on statistical data on a country scale. For more precise and realistic modeling, three explanatory variables (domestic use of fresh water, gross domestic product per capita and gross capital formation expenditure per capita) for water accessibility assessment and seven explanatory variables (the annual average temperature, the house connection to water supply, the house connection to sanitation, average dietary energy consumption, undernourished population rate, Gini coefficient of dietary energy consumption, and health expenditure per capita) for the health damage ssessment were chosen and non-linear multiple regression analyses were conducted.

Results Water accessibility could be modeled by all three explanatory variables with sufficient explanatory power (R^2=0.68). For the health damage assessment, significant explanatory variables were different from those for diseases, but the R^2 values of the regression models for each infectious disease were calculated as more than 0.4. Furthermore, the house connection to water supply rate showed a high correlation with every infectious disease. This showed that domestic water scarcity is strongly linked to health damage caused by infectious diseases. Based on the results of the regression analyses, the calculated damage factors of domestic water scarcity ranged from 1.29E-11 to 1.81E-03 [Disability Adjusted Life Years (DALYs)/m^3], and the average value (weighted mean value by domestic use of fresh water for each country) was 3.89E-07 [DALYs/m^3] and the standard deviation of damage factors was 1.40E-07 [DALYs/m^3].

Discussion According to the calculated damage factors for each country, countries sensitive to domestic water scarcity appeared to be located in the African region, and in addition, the amount of available domestic water tended to be less in the most sensitive countries. Water production technologies represented by desalination are expected to be a countermeasure for the reduction of water stress. As an example of the application of damage factor analysis, health damage improvement compared with the effects of CO_2 emission caused by the introduction of desalination plants showed that there were several countries where desalination

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was worth introducing after considering the advantages and disadvantages of the environmental impact.

Conclusions Damage assessment models of domestic water scarcity were developed by applying non-linear multiple regression analysis. Damage factors could be calculated for most countries, except for those without statistical data for the analysis. Damage factors are applicable to not only the assessment of water consumption, but also the evaluation of benefits of water production in countries suffering from water scarcity.

Recommendations and perspectives The analyses of this study were conducted by applying data on a country scale, and the regional and local characteristics within each country are expected to be taken into account in future studies. The water resource amount, which was represented by the amount of domestic use of fresh water in this study, should be estimated with consideration of the effects due to climate change.

Keywords Damage assessment · Desalination · Domestic water · Health damage · Infectious diseases · LCIA · Water scarcity

1 Background, aim, and scope

Water is a necessary resource for life on Earth. It is renewable through the water cycle, but a shortage can be caused by consumption in excess of the circulation rate. Furthermore, as with other resources, water is unevenly distributed throughout the world. Although the sensitivity may be different from area-to-area, water scarcity could occur anywhere in the world.

Sensitivity to deficiency in water resources seems to be particularly high in countries/areas with rapidly increasing populations. A UNESCO report (UNESCO 2003) indicated a growth of water demand in the world (1.4 times higher in 2025 than in 1995), with particularly remarkable growth in the Asian and African areas. In these areas, in addition to the population growth, there are many developing countries, and the deficiency of water resources may be accelerated by the inadequate economic power for preparing water supply systems and the increasing demand for water because of the migration of industrial activities from developed countries. From the viewpoint of globalization of production activities, even if sensitivity to water scarcity is low in a country, production and consumption activities in that country may indirectly affect on the scarcity of water resources in other countries through import of goods and services.

To minimize the environmental effects caused by water consumption in water-scarce countries, the introduction of a water supply system and the application of water production technologies are desirable. The environmental aspects of water production technologies and water supply systems have been assessed based on life cycle impact assessment (LCIA) in several previous studies; for example, an assessment of desalination technologies (Raluy et al. 2005a), comparisons of different water production technologies (Raluy et al. 2005b; Stokes and Horvath 2006) and an assessment of whole tap water supply systems (Laussaux et al. 2007). In these previous studies, only the negative environmental aspects of applying water production and supply systems were considered; and many of them did not evaluate the environmental benefits of creating water resources in water scarce areas.

The benefits (avoidable environmental effects) of creating water resources differ according to water use. The use of water for human activities can be generally classified into three types, domestic, agricultural, and industrial use. The lack of water for each use leads to various effects, such as agricultural/industrial productivity loss and intake of polluted water. In particular, the shortage of domestic water is one of the most serious problems in water scarce countries. The World Health Organization (WHO) reported that around 10% of the total burden of diseases in the world could be prevented by improvements related to drinking water, sanitation, hygiene, and water resource management (Prüss-Üstün et al. 2008). Creation of water resources could certainly result in environmental benefits through the improvement of human health, but water consumption may increase the risk of environmental damage. The methodology to assess the effect of domestic water scarcity[1] (low accessibility to safe water[2]) will be available to evaluate both environmental benefits of domestic water creation and the risk of environmental damage due to the lack of domestic water.

As it was pointed out in a previous review article (Koehler 2008), several current LCIA methods focused on the quantitative aspects of water resources. Characterisation factors to assess freshwater depletion at midpoint level are provided by the Swiss Ecological Scarcity (Frischknecht et al. 2009) and Milà i Canals et al. (2009). Alternative indicators for assessing the direct impact caused by water consumption, like the cumulative exergy demand indicator (Bösch et al. 2007; Dewulf et al. 2007) and the backup technology (Steward and Weidema 2005), have been proposed. A framework for more directly assessing the impact of water use in LCA also has been proposed by

[1] Domestic water scarcity is defined in this article as "low accessibility to safe water for drinking". It will be accelerated by water consumption.

[2] "Safe water" in this article is defined as "improved sources of drinking-water" (piped water into dwelling, piped water to yard/plot, public tap or standpipe, tubewell or borehole, protected dug well, protected spring, rainwater) according to the definition by WHO/UNICEF Joint Monitoring Program (WHO-UNICEF 2010).

Bayart et al. (2010) and the specific methodology to assess the damage to human health (malnutrition), to ecosystem quality (the loss of Net Primary Production), and to resources (surplus energy for future availability of water resource) caused by freshwater consumption has been developed by Pfister et al. (2009). The methodology developed by Pfister et al. (2009) is available for assessing the effect of malnutrition, NPP loss, and surplus energy demand. However, their methodology is not suitable in the case of assessing the damage caused by domestic water consumption because domestic water scarcity will cause different damage from their targets in their methodology.

Domestic water scarcity could lead to the spread of several infectious diseases. Unsafe water, poor sanitation, and hygiene are said to contribute to the spread of several diseases, particularly infectious and parasitic diseases such as diarrhea, trachoma, schistsomiasis, ascariasis, trichuriasis, hookworm disease, malaria, and Japanese encephalitis (Howard and Bartram 2003). The relationship between domestic water quantity and diarrhea incidence have been discussed in several previous studies (Esrey et al. 1985, 1992; Herbert 1985; Gorter et al. 1991; Esrey 1996). Some of them (Esrey et al. 1985; Gorter et al. 1991) showed that the improvement of domestic water availability seemed to be the most important factor in reducing diarrhea incidence, while others suggested that the improvement of sanitation would be more significant for the prevention of diarrhea (Esrey et al. 1992; Esrey 1996). Another study showed that the effectiveness of water availability improvement might depend on the age of inhabitants (Herbert 1985). The conditions in the target areas of these studies were different, so the effectiveness of only improving domestic water quantity is not directly comparable. Although the influence of water availability on infectious diseases might differ from area-to-area, these previous studies certainly indicated that domestic water quantity is an important factor in preventing infectious diseases. Thus, it is necessary to evaluate quantitatively the effects of changes in domestic water quantity on infectious diseases. An objective of this study is to model the relationship between the available quantity of domestic water and health damage caused by infectious diseases. In order to take other factors relating to infectious disease damage into account, multiple regression analyses were conducted by applying statistical data on a country scale.

2 Materials and methods

2.1 Assessment flow of health damage related to domestic water scarcity

An insufficient quantity of domestic water will bring about loss of accessibility to safe water, and subsequently contact with infectious sources will lead to the spread of infectious diseases. Thus, the assessment model of infectious disease damage related to domestic water scarcity is assumed to be composed of following two modules: the first one is a water accessibility assessment module describing the relationship between available domestic water quantities and accessibility to safe water, and the other is a health damage assessment module describing the relationship between accessibility to safe water and health damage caused by infectious diseases. In each module, regression analyses were conducted to model these relationships. Details of the regression analysis for each step will be explained in the following section.

As mentioned in the above section, there are several infectious diseases attributed to the loss of accessibility to safe water (Howard and Bartram 2003). Oral intake of safe water is necessary for hydration of human, but it is still severely restricted in areas suffering from water scarcity. Therefore, water scarcity seems to firstly lead to the oral intake of unsafe water. In this study, oral infectious diseases were focused on as target diseases. Quantitative data on health damage are necessary to evaluate the damage to health caused by infectious diseases. Disability Adjusted Life Years (DALYs) is a good indicator to use, because it is widely recognized as a health indicator and the WHO officially used DALYs in the publication of health statistic data. Among infectious diseases likely to be the result of water scarcity, DALYs data were disclosed only for diarrhea and intestinal nematode infections (ascariasis, trichuriasis, and hookworm disease). These four infectious diseases were selected as targets in this study.

2.2 Parameters for regression analysis

In modeling relationships among water scarcity, accessibility to safe water and damage to health caused by infectious diseases, parameters accounting for each condition need to be defined. Domestic use of fresh water and the house connection to water supply were set as parameters indicating water scarcity and accessibility to safe water, and statistical data on a country scale were obtained from the database of The World's Water (2008) and the WHO (2008a), respectively. As stated in the above section, DALYs (WHO 2008b) was selected as a parameter representing infectious disease damage.

In modeling the water accessibility module, the demand of domestic water, represented by domestic use of fresh water, will certainly affect on the house connection to water supply, but there might be other factors. In particular, the economic power for provision of infrastructure seems to influence the level of water supply service. Therefore, gross domestic product (GDP) per capita and gross fixed capital formation expenditure per capita were included as explanatory variables of the water accessibility module, and data

for each indicator were obtained from the database of The World Bank (2007).

Infectious disease damage will also depend on several factors besides the house connection to water supply. First, the source of infection needs to be generated. Generation of infectious sources will be dependent upon temperature, and so annual average temperature (World Meteorological Organization 2008) was included as one of the explanatory variables. Second, contact with infection sources will lead to the occurrence of infectious incidences. Exposure to infection sources will be dependent upon accessibility to safe water. Therefore, in addition to the house connection to water supply, the house connection to sanitation (The World's Water 2008) was also included as an explanatory variable. Third, if people accessing unsafe water have good enough nutrition and enough medical treatment, they will be able to reduce the extent of damage caused by infectious diseases. The indicators defined for average nutrient condition were average dietary consumption and undernourished population rate (FAO 2008). In addition, in order to highlight the gaps in nutrient conditions, the Gini coefficient of dietary energy consumption (FAO 2008) was also included as an explanatory variable. Medical treatment conditions were thought to be accounted for by health expenditure per capita (The World Bank 2007). The above-mentioned seven indicators including the house connection to water supply were set as explanatory variables for multiple regression analysis for modeling the health damage assessment module.

Statistical data for each indicator used for the analyses should be consistent for the time when data were collected. DALYs data available for the analyses were only published for 2002. We defined 2002 as the standard year for the analyses and data of other indicators in 2002 or the nearest year were collected.

2.3 Procedures of regression analysis

Based on the data collected, multiple regression analyses were performed to develop the water accessibility assessment module and health damage assessment module. For both modules, the relationship between subjective and explanatory variables may not always be a linear relationship. Thus, non-linear regression analysis was applied to model them. The regression analyses were conducted as follows:

1. Data cleansing: in addition to lack of data, outlier data were excluded from the analyses by performing a Smirnov–Grubbs test.
2. Determination of regression line shapes: five typical line shapes (linear, exponential, cumulative power, logarithmic, logistic) were defined and single regression analyses were performed for subjective and explanatory variables.
3. Multiple regression analysis: regression formulas with the highest R^2 values in single regression analyses were combined to independently describe multiple regression formulas and subsequently multiple regression analyses were conducted. The backward step was applied for the multiple regression analyses to identify statistically significant explanatory variables. Criteria for the selection of explanatory variables are set as (1) F value should be more than 2.0, (2) P value should be less than 0.05 (95% significance), and (3) adjusted R^2 value of regression formula should be larger than that in the former step.

3 Results and discussions

3.1 Water accessibility assessment

For modeling the water accessibility assessment module, single regression analyses were performed for the house connection to water supply and three explanatory variables (domestic use of fresh water [m^3/capita/year], GDP per capita [US$/capita: PPP] and gross fixed capital formation expenditure per capita [US$/capita: PPP]). The results (R^2 values) of single regression analyses for each explanatory variable are shown in Table 1. The optimal line shapes were determined based on the results as logistic for domestic use of fresh water, logarithmic for GDP per capita, and logistic for gross fixed capital formation expenditure per capita.

According to the results of single regression analyses, the multiple regression formula could be constructed as follows Eq. 1:

$$\text{The house connection of water supply } [\%] = a_1/(1 + b_1 \times \mathrm{Exp}(c_1 \times X_1)) + a_2 \times \mathrm{Ln}(X_2) + a_3/(1+b_3 \times \mathrm{Exp}(c_3 \times X_3)) + K \quad (1)$$

where X_1 is domestic use of fresh water [m^3/capita]; X_2 is GDP per capita [US$/capita/year]; X_3 is gross fixed capital formation expenditure per capita [US$/capita/year]; a_1, a_2, a_3, b_1, b_3, c_1, and c_3 are constant coefficients.

Based on the above formula, multiple regression analysis was conducted. The t values, P values, and variable inflation factors (VIF) obtained for each explanatory variable are presented in Table 2.

As shown in Table 2, all assumed explanatory variables show high t values, and P values for each variable are lower than 0.05, which means that all variables have statistically significant relationships with the house connection to water supply. VIF values of all explanatory variables range from

Table 1 R^2 values for each line shape obtained from single regression analyses for water accessibility assessment

	Linear	Exponential	Cumulative power	Logarithmic[a]	Logistic
Domestic use of fresh water	0.343	0.318	0.386	N.A.	0.476
GDP per capita	0.379	0.337	0.618	0.641	0.590
Gross fixed capital formation expenditure per capita	0.374	0.343	0.561	0.567	0.593

[a] Logarithmic could not be applied to variables with data including zero value

1.3 to 4.4 (lower than general criteria (VIF>_10) of multi-correlation). Thus, multi-correlation among explanatory variables cannot be found. Furthermore, R^2 value of the multiple regression formula was calculated as 0.68 (N=131). Thus, partial differentiation of Eq. 1 for the first term was conducted Eq. 2:

$$\text{Water accessibility difference} \quad (2)$$
$$\left[\%/\left(\mathrm{m}^3/\text{capita/year}\right)\right] = 4.6\mathrm{E}-07\times\mathrm{Exp}(0.00016\times \mathrm{X}_1)/\left(1-0.99\times\mathrm{Exp}(0.00016\times\mathrm{X}_1)\right)^2$$

Equation 2 is the water accessibility assessment module, which describes the difference in the house connection to water supply caused by a unit change of domestic use of fresh water.

3.2 Health damage assessment

To model the health damage assessment module, optimal line shapes (linear, cumulative power, exponential, logarithmic, and logistic) were determined based on single regression analyses for health damage data (DALYs) of each infectious disease and seven explanatory variables (the annual average temperature [°C], the house connection to water supply [%], the house connection to sanitation [%], average dietary consumption [kcal/capita/day], undernourished population rate [%], the Gini coefficient of dietary energy consumption [%] and health expenditure per capita [US$/capita: PPP]). More detail results of single regression analyses are available in the Electric Supplementary Material (see Section 2). Based on the optimal line, shapes determined for each relationship between each disease and explanatory variable, multiple regression analysis was performed for each infectious disease. Relationships between each infectious disease and explanatory variables are summarized in Tables 3, 4, 5, and 6, shown as line shapes, t values, P values, and VIF values.

The statistical significance of the house connection to water supply for every infectious disease was determined as shown in Tables 3, 4, 5, and 6. In addition, t values of the house connection to water supply for each infectious disease were relatively higher. This suggests that accessibility to safe water seemed to be one of the most important factors in infectious disease health damage. VIF values of all explanatory variables to be statistically significant range from 1.2 to 2.4 (lower than general criteria (VIF>_10) of multi-correlation). Thus, multi-correlation among explanatory variables cannot be found. According to the results of multiple regression analysis, health damage for each infectious disease could be described as follows:

$$\text{Ascariasis damage} \quad (3)$$
$$\left[\times10^{-7}\mathrm{DALY/capita}\right]= 15.5\times\mathrm{Exp}(-0.0466\times \mathrm{Z}_1) -6.95/(1-30.4\times\mathrm{Exp}(-16.8\ \mathrm{Z}_2))+0.0383\times(\mathrm{Z}_3)^{4.72}-6.58$$

$$\text{Trichuriasis damage} \quad (4)$$
$$\left[\times10^{-7}\ \mathrm{DALY/capita}\right] = -0.0152\times \mathrm{Z}_2 -3.20\times\mathrm{Ln}(\mathrm{Z}_4)+13.2$$

Table 2 The results of multiple regression analysis for water accessibility assessment (estimated parameters, line shape, t values, P values, and FIV values of each explanatory variable)

	Parameters				Line shape	t value (P value)	FIV
	a	b	c	K			
Domestic use of fresh water	0.0028	−0.99	0.00016	–	Logistic	3.05 (0.00)	1.25
GDP per capita	8.9	–	–	–	Logarithmic	5.85 (0.00)	4.35
Gross fixed capital formation expenditure per capita	9.7	−5295	−0.016	–	Logistic	2.63 (0.01)	3.56
Constant term	–	–	–	2.00		18.4 (0.00)	

Adjusted R^2: R^{*2} =0.68 (N=131)

Table 3 Relationships between ascariasis damage and explanatory variables obtained by multiple regression analyses

	Line shape	*t* value (*P* value)	FIV
Annual average temperature: Z_1	Exponential	2.23 (0.03)	1.22
House connection rate to water supply: Z_2	Exponential	5.80 (0.00)	1.52
House connection rate to sanitation: Z_3	Cumulative power	2.52 (0.01)	1.17
Average dietary energy consumption: Z_4			
Undernourished population rate: Z_5			
Gini coefficient of dietary energy consumption: Z_6			
Health expenditure per capita: Z_7			

Adjusted R^2 : R^{*2} =0.41 (N=85)

Hookworm disease damage (5)

$$\left[\times 10^{-7}\ \mathrm{DALY/capita}\right] = -0.00288 \times \mathrm{Z}_2 + 1.40 \times (1 - 1.40 \times \mathrm{Exp}(0.00730 \times \mathrm{Z}_3) + 3.50$$

Diarrhea damage (6)

$$\left[\times 10^{-7}\mathrm{DALY/capita}\right] = 553.9 \times (\mathrm{Z}_2)^{-0.498} + 227.0 \times \mathrm{Ln}(\mathrm{Z}_4) + 21.2 \times\ \mathrm{Z}_6 + 463.6$$

where Z_1 is the annual average temperature [°C]; Z_2 is the house connection to water supply [%]; Z_3 is the house connection to sanitation [%]; Z_4 is the average dietary energy consumption [kcal/capita/day]; Z_5 is the undernourished population rate [%]; Z_6 is the Gini coefficient of dietary energy consumption [%]; and Z_7 is the health expenditure per capita [US$/capita: PPP]. The health damage assessment module could be obtained by performing partial differentiation of the above four formulas Eqs. 3–6 for Z_2. The obtained module predicted the damage to health caused by a unit change in the house connection to water supply.

Table 4 Relationships between trichuriasis damage and explanatory variables obtained by multiple regression analyses

	Line shape	*t* value (*P* value)	FIV
Annual average temperature: Z_1			
House connection rate to water supply: Z_2	Linear	4.12 (0.00)	1.69
House connection rate to sanitation: Z_3			
Average dietary energy consumption: Z_4	Logarithmic	4.63 (0.00)	1.75
Undernourished population rate: Z_5			
Gini coefficient of dietary energy consumption: Z_6			
Health expenditure per capita: Z_7			

Adjusted R^2 : R^{*2} =0.44 (N=104)

Table 5 Relationships between Hookworm disease damage and explanatory variables obtained by multiple regression analyses

	Line shape	*t* value (*P* value)	FIV
Annual average temperature: Z_1			
House connection rate to water supply: Z_2	Linear	5.67 (0.00)	2.40
House connection rate to sanitation: Z_3	Logistic	3.28 (0.00)	2.04
Average dietary energy consumption: Z_4			
Undernourished population rate: Z_5			
Gini coefficient of dietary energy consumption: Z_6			
Health expenditure per capita: Z_7			

Adjusted R^2 : R^{*2} =0.52 (N=114)

3.3 Damage factors in each country

By combining the water accessibility assessment module and the health damage assessment module, the damage factors for each country that describe infectious disease damage to health caused by the shortage of a unit volume of domestic water can be calculated based on the data of domestic fresh water use in each country. A distribution map of the calculated damage factors showing total damage of infectious diseases in each country is given in Fig. 1. For both diarrhea and intestinal nematode infections, countries that are particularly sensitive to water shortage are mainly found in the Africa and Asia. In Fig. 2, the relationship between damage factors of total damage related to diarrhea and intestinal nematode infections and domestic use of fresh water per capita are shown. The decreasing tendency of damage factors with increasing domestic use of fresh water per capita can be clearly seen. This shows that water scarce regions are more sensitive to water shortage.

The frequency distribution of damage factors for total damage caused by infectious diseases in each country is shown in Fig. 3. The damage factors of most countries

Table 6 Relationships between diarrhea damage and explanatory variables obtained by multiple regression analyses

	Line shape	*t* value (*P* value)	FIV
Annual average temperature: Z_1			
House connection rate to water supply: Z_2	Cumulative power	6.87 (0.00)	2.41
House connection rate to sanitation: Z_3			
Average dietary energy consumption: Z_4	Logarithmic	3.65 (0.00)	1.70
Undernourished population rate: Z_5	Linear	3.74 (0.00)	1.66
Gini coefficient of dietary energy consumption: Z_6			
Health expenditure per capita: Z_7			

Adjusted R^2 : R^{*2} =0.67 (N=106)

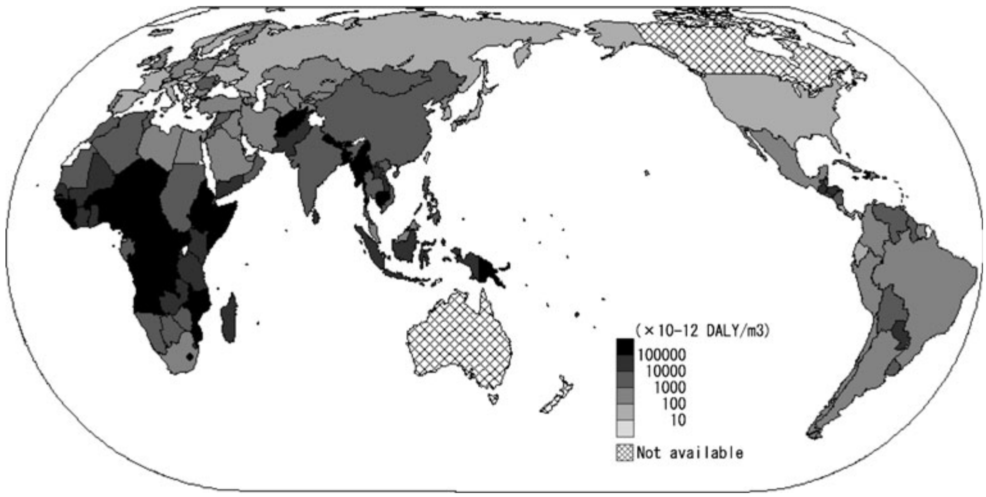


Fig. 1 Distribution map of calculated damage factors in the world

range from 1.29E-11 to 1.81E-03 [DALYs/m^3], almost 98% countries in the range of 10^{-11} to 10^{-6}. World average damage factor of infectious diseases related to water scarcity was calculated as 3.89E-07 [DALYs/m^3], weighted mean value by domestic use of fresh water for each country. The value of standard deviation of damage factors was calculated as 1.40E-07 [DALYs/m^3].

3.4 Example of application to the assessment of desalination technology

Water production technology represented by desalination will contribute to the reduction of the stress related to the shortage of water. However, the introduction of water production technology may lead to an increase in other types of environmental impacts caused by energy/material consumption, CO_2, and other harmful substance emissions. Using the present LCIA methodologies, only negative aspects of environmental effects could be assessed. However, damage factors of water scarcity estimated in this study will make it possible to evaluate the advantage of introducing water production technologies to water scarce countries from the viewpoint of environmental effects.

For example, CO_2 emissions per unit volume water production by the introduction of typical desalination technologies (multi-stage flash, multi-effect desalination, reverse osmosis) were reported as ranging from 0.08 to 3.27 [kg-CO_2/m^3] (Raluy et al. 2005a, b). Health damage caused by CO_2 emissions can be evaluated as 1.62E-07 [DALYs/kg-CO_2] based on the LIME methodology (Itsubo et al. 2003) and 2.10E-07 [DALYs/kg-CO_2] based on Eco-indicator 99 (Pre Consultants 2001). The health damage of the introduction of desalination technology can be calculated as ranging from 0.13E-07 to 6.87E-07 [DALYs/m^3]. If the damage factors of each country were larger than the calculated damage caused by CO_2 emissions, it can be said that desalination technologies are effective for the prevention of damage to health from the viewpoint of CO_2 emissions and water scarcity. Countries where it would be worth introducing desalination technology are mapped in Fig. 4. More than 22 countries (maximum: 50 countries), mainly located in the African region, would seem to benefit from introducing desalination technologies. However, the advantage of desalination technologies is discussed here only in the aspect of health damage related to CO_2 emission and the shortage of domestic water. It is necessary to consider various types of environmental impacts (abiotic/biotic resource depletion, air/water/soil pollution, etc.) for more strict discussions on the validity of introducing desalination technologies.

4 Conclusions and perspectives

Water is an indispensable resource for our life, but there were not any quantitative assessment methodologies for

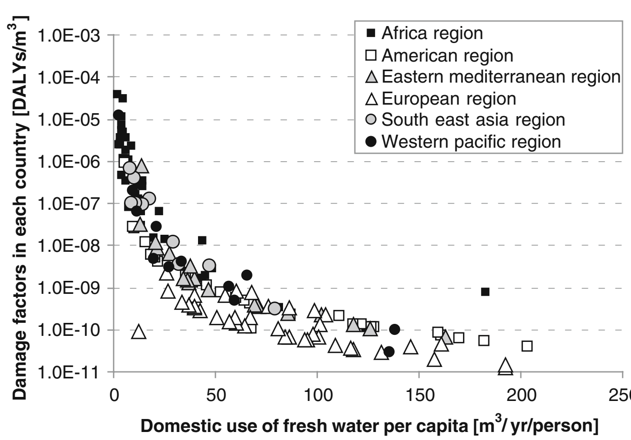


Fig. 2 Relationship between domestic use of fresh water per capita and damage factors in each country

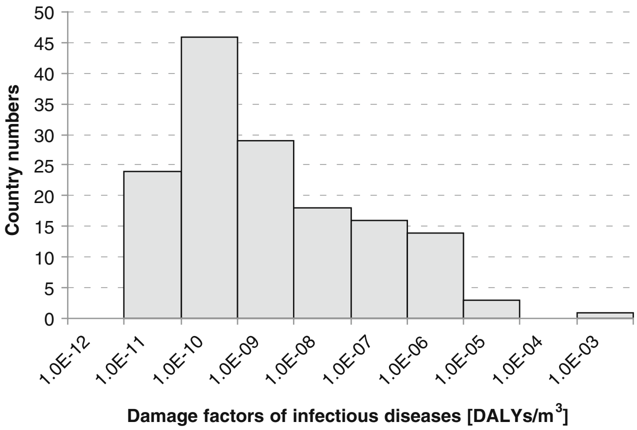


Fig. 3 Frequency distribution of damage factors for each country

domestic water scarcity. In this study, we proposed a methodology for modeling the assessment of the damage to health of infectious diseases caused by domestic water scarcity based on multiple regression analysis of statistical data.

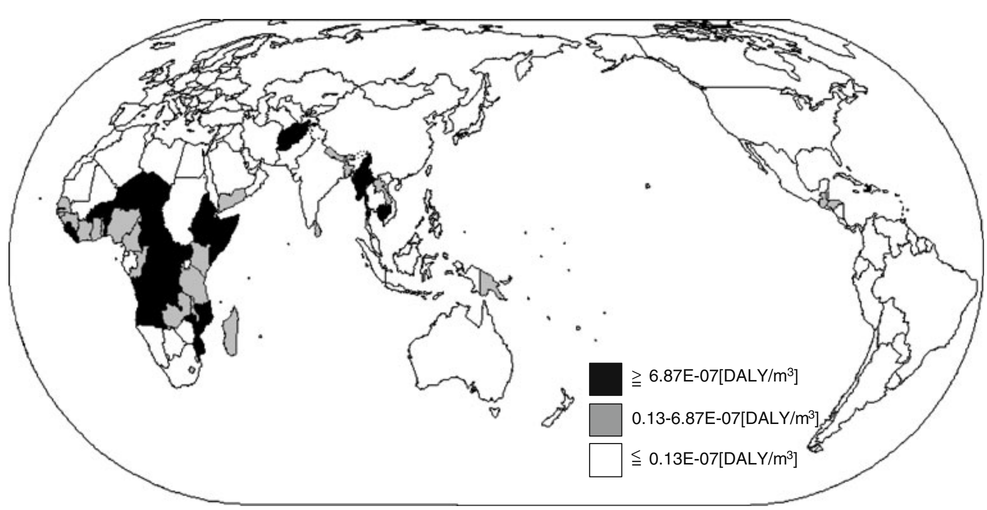
The cause–effect chain of domestic water scarcity was defined by two steps, accessibility loss to safe water and damage to health caused by the intake of unsafe water. Water accessibility could be explained by three variables, domestic use of fresh water, GDP per capita, and gross fixed capital formation expenditure per capita. Every explanatory variable was statistically significant and the model showed sufficient explanatory power (R^2=0.68).

Infectious damage to health was explained by the annual average temperature, the house connection to water supply, the house connection to sanitation, average dietary energy consumption, and the Gini coefficient of dietary energy consumption in each country. In particular, the house connection to water supply showed a high correlation to all target infectious diseases (ascariasis, trichuriasis, hookworm disease, and diarrhea), which suggested that a supply of safe water was one of the most important and sensitive factors for controlling infectious disease damage.

The damage factors calculated for domestic water scarcity appeared to be higher in the African region. Countries sensitive to domestic water scarcity tend to lack of sufficient and safe water resources (see Fig. 2). Water production technologies will result in increased environmental impact relating to material and energy consumption such as CO_2 emission, but several countries showed benefits in the introduction of desalination technology from the viewpoint of the comparison between the health impacts related to CO_2 emissions and the shortage of domestic water. The model for the assessment of domestic water scarcity and damage factors will be applicable to the evaluation of water production technologies.

There are still several areas for improvement in future studies. While some explanatory variables appeared to be not statistically significant with the damage of infectious diseases, it cannot be easily concluded that these variables do not affect infectious diseases based on only the results of regression analyses. All data used in this analysis were on a country scale, but the situation within each country will be different from region to region. The analyses based on more regional and local data are needed in the future. In this study, domestic use of fresh water represented domestic water resource amounts in each country because the estimation of the amount of domestic water resource is quite difficult and no information was available. However, the estimation of water resource amounts is necessary for more precise assessment. In addition, climate change will also affect water resource distribution in the world. Dynamic changes of water resources caused by climate change should be also taken into account in order to reflect a more realistic situation.

Fig. 4 Countries (*black* and *gray*) which could benefit from the introduction of desalination technologies in terms of damage to health



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